
Jäger, Gerd:

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Precision Mechatronics – Nanomeasuring and Nanopositioning Engineering at the Technische Universität Ilmenau

Gerd Jäger

Technische Universität Ilmenau

Institute of Process Measurement and Sensor Technology

P.O.Box 100 565, 98684 Ilmenau, Germany

gerd.jaeger@tu-ilmenau.de

Abstract:

In the paper is proposed to use the term Precision Mechatronics for a new generation of high precision systems and machines.

High precision systems and machines are technological equipment for positioning, measurement, scan, modification, treatment and manipulation of objects at nanometre scale over macroscopic distances.

The paper describes a precision mechatronic machine with integrated nanoprobes. This device represents a long range three-dimensional nanopositioning and nanomeasuring machine (NPM-Machine) having a resolution of 0,1 nm over the range of 25 mm x 25 mm x 5 mm.

An Abbe offset-free design of three miniature plan mirror interferometers and applying a new concept for compensating systematic errors resulting from mechanical guide systems provide very small uncertainties of measurement. The NPM-Machine has been developed by the Institute of Process Measurement and Sensor Technology of the Technische Universität Ilmenau and manufactured by the SIOS Messtechnik GmbH Ilmenau. The machines are operating successfully in several German and foreign research institutes including the Physikalisch-Technische Bundesanstalt (PTB), Germany.

The integration of several, optical and tactile probe systems and nanotools makes the NPM-Machine suitable for various tasks, such as large-area scanning probe microscopy, mask and wafer inspection, nanostructuring, biotechnology and genetic engineering as well as measuring mechanical precision workpieces, precision treatment and for engineering new material. Various developed probe systems have been integrated into the NPM-Machine. The measurement results of a focus sensor, metrological AFM, white light sensor, tactile stylus probe and of a 3D-micro-touch-probe are presented.

Single beam-, double beam- and triple beam interferometers built in the NPM-Machine for six degrees of freedom measurements are described.

1. Introduction

If one believed in the prediction made by Gordon Moore according to which the number of transistors on a chip doubles every two years, more than one thousand million transistors would have to be realized per chip in the year 2010. The consequences of this are that 45-nm structures will have to be implemented.

However, the technological development will not have reached its ultimate destination yet. The way afterwards is depicted by the “Technology Roadmap for Semiconductors 2003”, which predicts that in the year around 2016, 22-nm structures will have to be realized.

In the face of those enormous technological objectives, high requirements will have to be fulfilled also by nanometrology just as by nanomeasuring- and nanopositioning techniques. Thus, scanning probe microscopes scanning over large areas are required for mask and wafer inspection and also for the testing of ICs, with those microscopes being suited to industrial applications, too. In addition, nanomeasuring- and nanopositioning devices are necessary for the positioning and measuring to within a nanometre of, for example, nanosurface- and nanostructure standards, mechanical and optical high-precision parts as well as for material analysis. A nanopositioning and nanomeasuring machine (NPM-Machine) presenting a relatively large positioning and measuring range of 25 mm x 25 mm x 5 mm and a resolution of 0,1 nm has been developed at the Institute of Process Measurement and Sensor Technology of the TU Ilmenau.

The structure and the operating principle of this machine, the integration of different sensor systems, and the measurements performed are explained.

2. Design and operation of the NPM-Machine

The objective is the development of highly capable, reliable nanopositioning and nanomeasuring instruments (NPM-Machines) at sub-nanometer scale across large ranges.

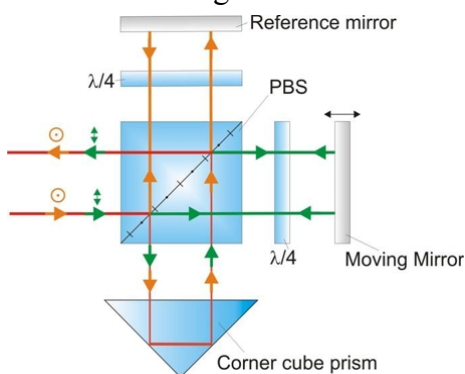
Our NPM-Machines [1, 2, 3] consist of following main components:

- traceable linear and angular measurement instruments at high resolution and accuracy
- 3D-nanopositioning stages (bearings, drives)
- nanoprobes (AFM, Focussensor, Metrological AFM, White light sensor, Tactile stylus probe) suitable for integration into NPM-Machine
- control equipment.

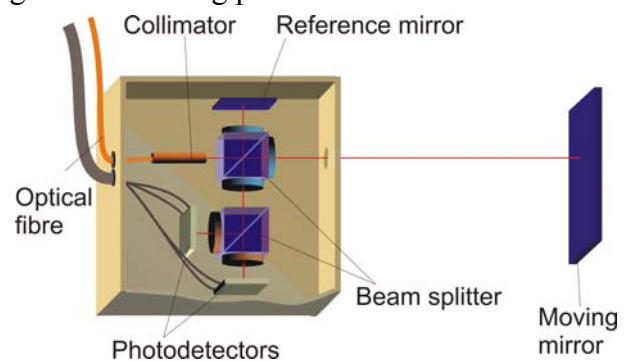
First of all a new concept is required to assemble the main components in order to achieve uncertainties as small as possible.

2.1 Traceable linear and angular sensors

Fig. 1 shows the difference between a plane mirror interferometer of the state of the art (left) and the interferometer developed by our institute (right) [4, 5]. The most advantage of our plane mirror interferometer is that it has only one measuring beam. This fact is important for compliance with the Abbe comparator principle on all three measurement axes. The interferometer (left) needs two beams for having tilt invariance in a small angle range of the moving plane mirror.



Plane mirror interferometer of the state of the art



Plane mirror interferometer developed by the Institute of Process Measurement and Sensor Technology

Figure 1: Plane mirror interferometers

Single, double and triple beam plane mirror interferometers can be applied in the NPM-Machine in order to measure the six degrees of freedom (see Fig. 2).

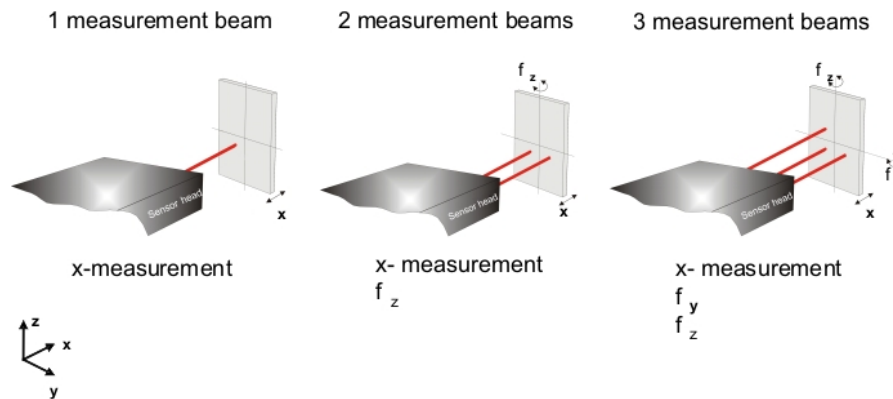
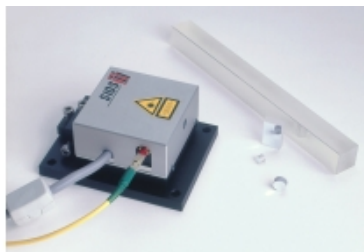


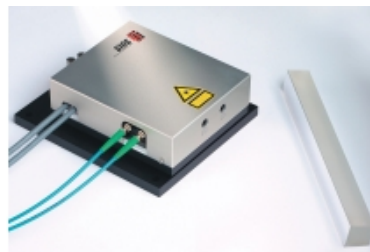
Figure 2: Single, double and triple beam plane mirror interferometer

Fig. 3 shows the photographs and the technical data of single, double and triple beam plan mirror interferometers.



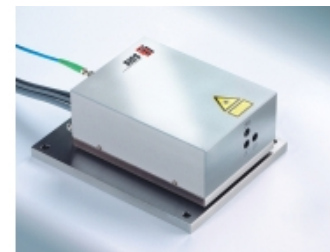
Single Beam Interferometer

Measurement range: 2 m
Resolution: 1 nm; 0,1 nm
Maximum moving-mirror translation rate: 600 mm/s



Double Beam Interferometer

Measurement range : 2 m
Resolution: 1 nm; 0,1 nm
Beam separation: 2...4, ≥ 10 mm
Angular measurement range : ± 2 arcmin
Angular resolution: 0,1...0,01arcsec
Angular measurement range with beam focussing: ± 30 arcmin



Triple Beam Interferometer

Measurement ranges: each axis 2 m
Resolution: 1 nm; 0,1 nm
Beam separations: 12 mm
Pitch and yaw measurement ranges: ± 2 arcmin
Angular resolution: 0,02 arcsec

Fig. 3: Technical data of the plan mirror interferometers

2.2 Operation of the NPM-Machine

The approach of the NPM-Machine consists of a consequent realization of the Abbe comparator principle in all the measurement axes at all times (see Fig. 4).

The intersection of all length measurement axes is the point of contact between the probe and the sample. This Abbe offset-free design with three interferometers and a user-selectable surface-sensing probe provides extraordinary accuracy. The sample is placed on a movable corner mirror that is positioned by three-axis drive systems. The position of the corner mirror is measured by three plane mirror interferometers. Angular deviations of the guide systems are measured at the corner mirror by means of sensitive angle sensors and used for angular control.

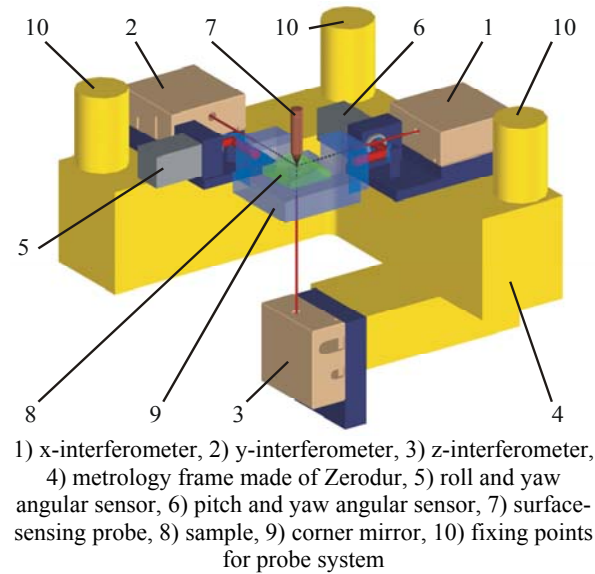


Figure 4: Abbe offset-free design of the NPM-Machine

Guide error compensation of the stages is achieved by a close-loop control system (Fig. 5). The used electromagnetic drives achieve high speed and, at the same time, a positioning resolution of less than 1 nm. The NPM-Machine has electromagnetic drives with one drive each for x- and y-axes and four drives for the z-axis. Therefore, the angular errors caused by the x- and y-axes of the linear guides can be compensated.

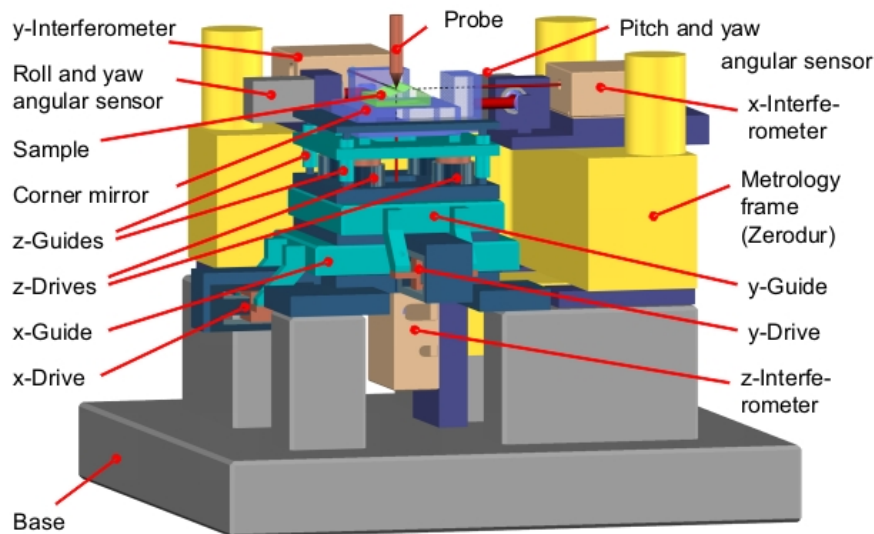


Figure 5: Mechanical and optical design on the NPM-Machine

2.3 Nanoprobes integrated into the NPM-Machine

Many different nano sensor types can be used for integration into the NPM-Machine. A focus sensor [6], a scanning force microscope, a metrological AFM, a white light sensor and a tactile stylus probe have been developed by the Institute of Process Measurement and Sensor Technology.

The central part of the focus sensor is a so-called hologram laser unit. This multifunctional element has made the extreme miniaturization of the sensor possible. The structure of the entire focus sensor is shown in figure 6.

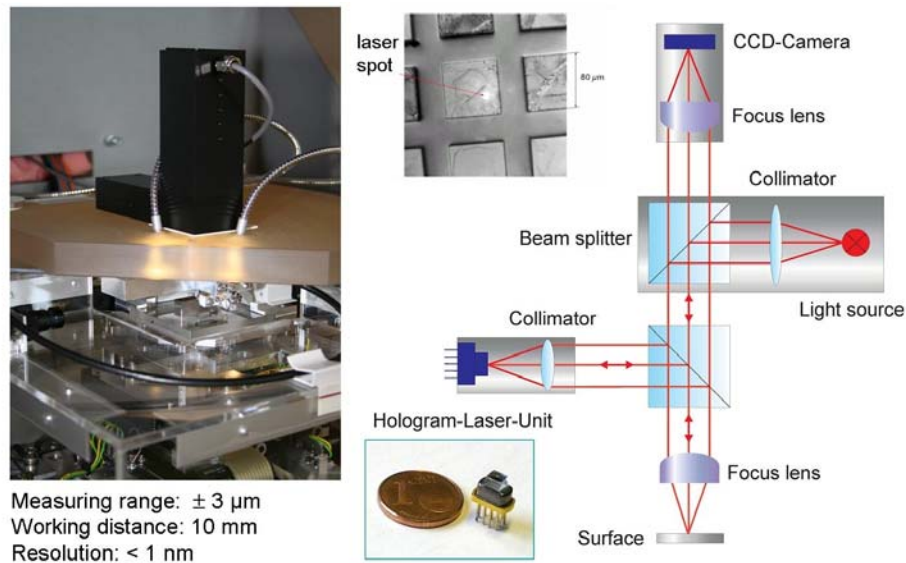


Figure 6: Setup for focus sensor

The lateral resolution is about $0,8 \mu\text{m}$. The resolution depends on the laser wavelength and the focal aperture of the probe. The optical system has been dimensioned such that a measurement range of about $\pm 3 \mu\text{m}$ can be achieved. Thus, a resolution of the zero point of $< 1 \text{ nm}$ is made possible by the AD converter used. The working distance is 10 mm. To be able to see the point of the optical scanning on the surface of the sample, the focus sensor has been combined with a CCD camera microscope, which allows the user to spot interesting regions on the sample surface. The camera illumination is fed from an LED via optical fibres to minimize heat penetration into the measuring machine. The characteristic line of the focus probe can be calibrated using the laser interferometer of the NPM-Machine.

The focus sensor has been used to design a scanning force microscope. The bending of the cantilever is detected by the focus sensor. Due to an integrated piezo translator, measurements in intermittent contact mode as well as in contact mode are possible (Fig. 7).

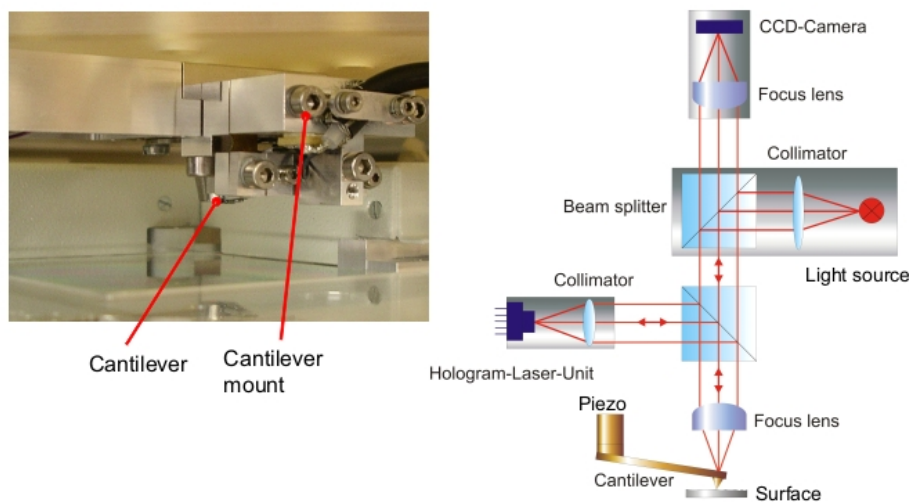


Figure 7: Scanning force microscope with focus sensor

A developed metrological AFM is the first AFM traced to international standards. The bending of the cantilever is measured by a plane mirror interferometer and the bending and torsion additional detected by a quadrant photo diode.

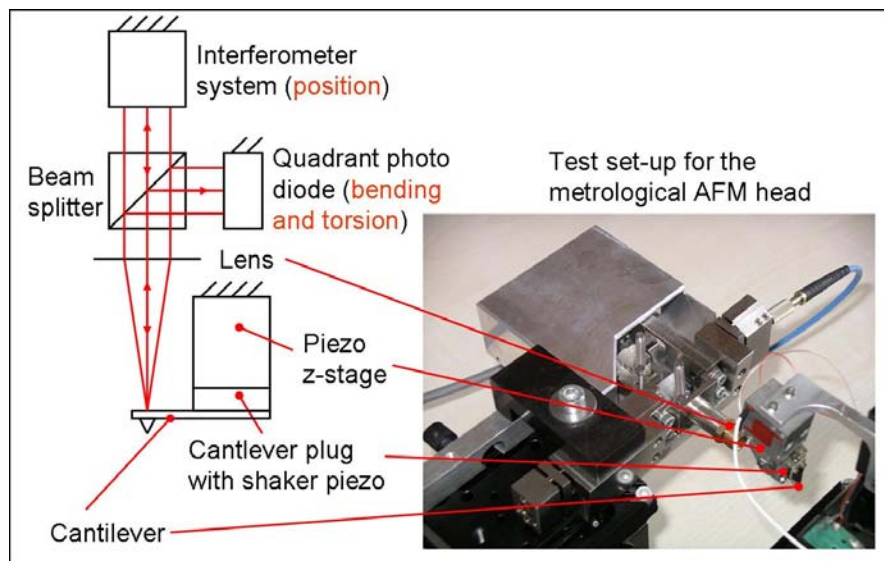


Fig. 8: Metrological AFM

A white light interferometer (Mirau-interferometer) was installed into the NPM-Machine for surface measurement having a field of view of $800\text{ }\mu\text{m} \times 600\text{ }\mu\text{m}$ (see Fig. 9). The white light interferometer has been combined with a CCD camera microscope.

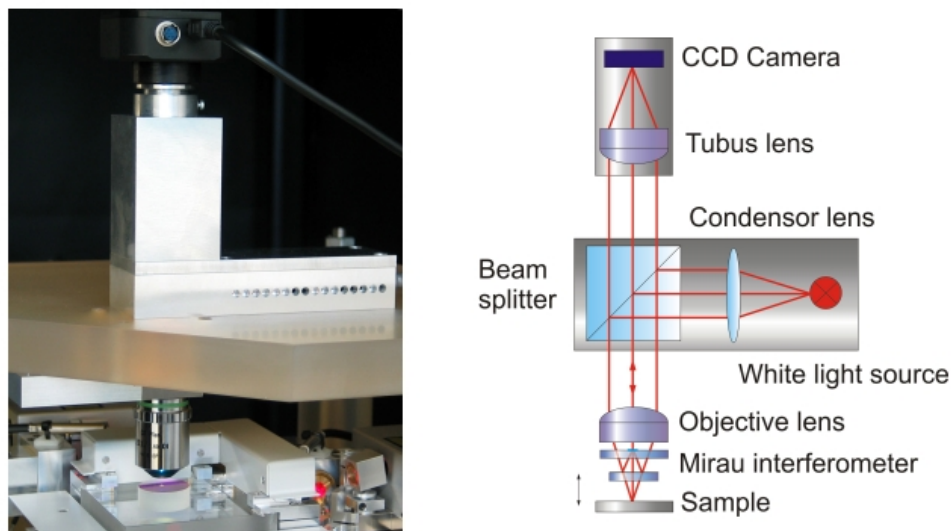


Fig. 9: White light interferometer

For the form measurement a tactile stylus probe has been developed. The zero-position of the stylus probe is detected by the focus sensor explained before. The stylus probe is illustrated in Fig. 10.

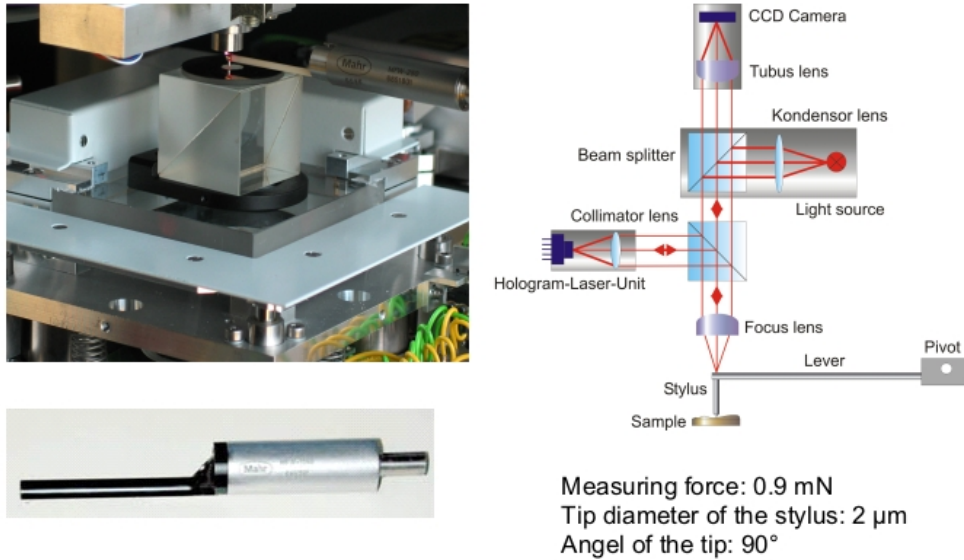


Fig. 10: Tactile stylus probe for form measurement

3. Measurement results

The most advantage of our NPM-Machine design unlike the CMM available on the market is that the x-, y- and z-ranges are realized by the 3D-positioning stage. Hence it follows that the nanoprobes have to work as zero-point sensor only. The zero-point position of all optical and mechanical probes is the most accurate one.

Step-height standards from 7 nm to 1 mm were measured using the NPM-Machine with integrated focus sensor. For example one step-height standard was measured with a height of 777,1 nm and an expanded uncertainty ($k = 2$) of only 2 nm. Fig. 11 represents the measurement result of a 1 mm step-height.

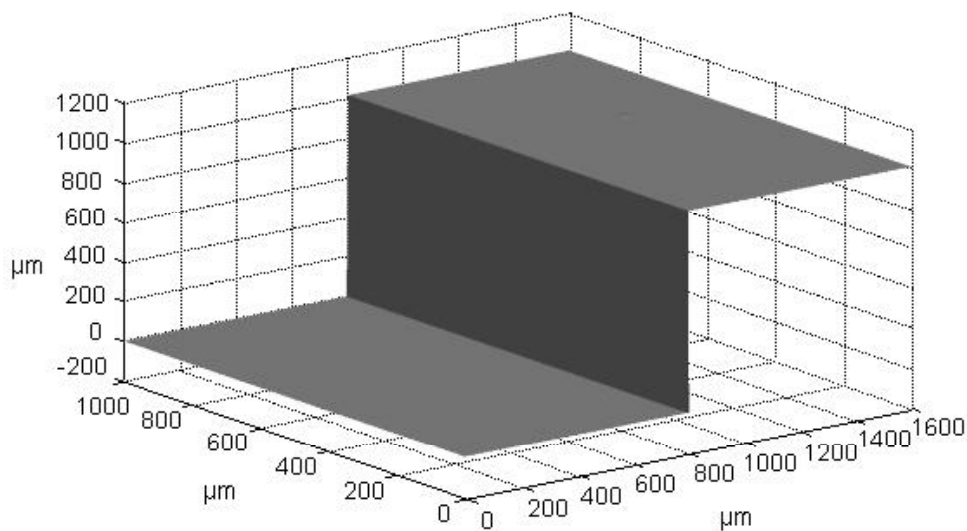


Fig. 11: 1mm step-height

Fig. 12 illustrated the long range nanoscale measurement of a aspherical lens.

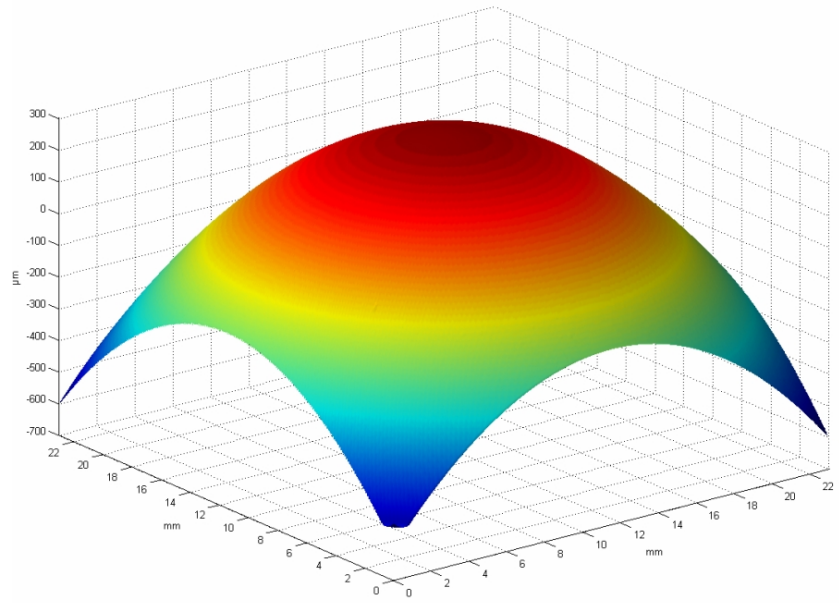
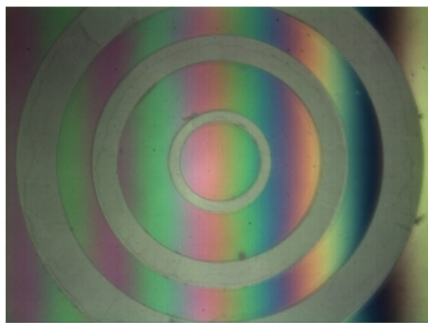
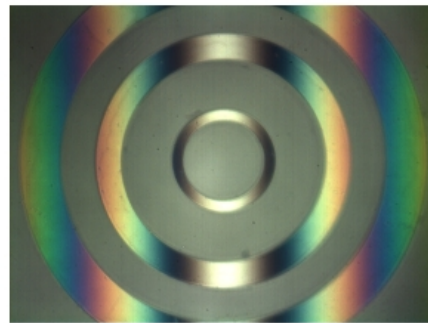


Fig. 12: Aspherical lens: $22 \times 22 \times 0,8 \text{ mm}^3$, scanning speed: 5 mm/s , 160.000 data points in $< 30 \text{ min}$

The Fig. 13 shows measurement results of a ring structure obtained with the NPM-Machine and the white light interferometer.



White light fringes



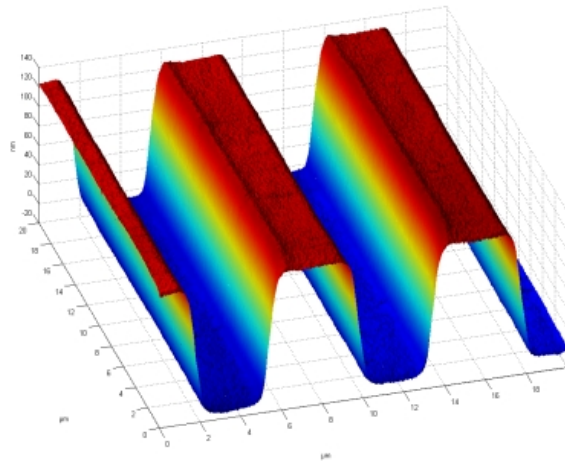
White light fringes on the top of the structure

Step height of the structure: 20 µm

Field of view: $800 \text{ µm} \times 600 \text{ µm}$; Resolution: $1600 \times 1200 \text{ pixel}$

Fig. 13: Measurements with the white light interferometer

The measurement result of a glas scale measured with the tactile stylus probe is shown in Fig. 14.



Glas scale for linear incremental encoder/ grating period: 8 μm

Fig. 14: Measurements using the tactile stylus probe

4. Acknowledgements

The authors wish to thank all those colleagues who have contributed to the developments presented here. Our special thanks are due to the Thuringian Ministry of Science, Research and Arts for promotion the nanocoordinate metrology in the framework of joint projects and the German Research Foundation (DFG) for funding the Collaborative Research Center 622 “Nanopositioning and Nanomeasuring Machines” at the Technische Universität Ilmenau.

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